Fiber Types in Gigabit Optical Communications

Abstract

Fiber optic cables are the medium of choice in telecommunications infrastructure, enabling the transmission of high-speed voice, video, and data traffic in enterprise and service provider networks. Depending on the type of application and the reach to be achieved, various types of fiber may be considered and deployed.

This paper describes the main characteristics of optical fiber in general, and the properties of multimode and single-mode fiber (MMF and SMF) in particular.

Brief History of Optical Communications

Table 1. The Optical Era

Date	Milestone
May 16, 1960	Theodore Maiman demonstrates first laser at Hughes Research Laboratories in Malibu
December 1960	Ali Javan makes first helium-neon laser at Bell Labs, the first laser to emit a steady beam
1962–63	Alec Reeves at Standard Telecommunications Laboratories in Harlow, United Kingdom, commissions a group to study optical waveguide communications under Antoni E. Karbowiak. One system they study is optical fiber.
Autumn 1962	Four groups nearly simultaneously make first semiconductor diode lasers, but they operate only pulsed at liquid-nitrogen temperature. Robert N. Hall’s group at General Electric is first
1963	Karbowiak proposes flexible thin-film waveguide
December 1964	Charles K. Kao takes over STL optical communication program when Karbowiak leaves to become chair of electrical engineering at the University of New South Wales. Kao and George Hockham soon abandon Karbowiak’s thin-film waveguide in favor of single-mode optical fiber
January 1966	Kao tells Institution of Electrical Engineers in London that fiber loss could be reduced below 20 decibels per kilometer for inter-office communications
April 1970	STL demonstrates fiber optic transmission at Physics Exhibition in London
Spring 1970	First continuous-wave room-temperature semiconductor lasers made in early May by Zhores Alferov’s group at the Ioffe Physical Institute in Leningrad (now St. Petersburg) and on June 1 by Mort Panish and Izuo Hayashi at Bell Labs
Summer 1970	Maurer, Donald Keck, Peter Schultz, and Frank Zimar at Corning develop a single-mode fiber with loss of 17 dB/km at 633 nanometers by doping titanium into fiber core
Late Fall 1970	Charles Kao leaves STL to teach at Chinese University of Hong Kong; Murray Ramsay heads STL fiber group
1971–1972	Unable to duplicate Corning’s low loss, Bell Labs, the University of Southampton, and CSIRO in Australia experiment with liquid-core fibers
1971–1972	Focus shifts to graded-index fibers because single-mode offers few advantages and many problems at 850 nanometers
June 1972	Maurer, Keck and Schultz make multimode germania-doped fiber with 4 decibel per kilometer loss and much greater strength than titania-doped fiber
Late 1972	STL modulates diode laser at 1 Gbit/s
1973	John MacChesney develops modified chemical vapor deposition process for fiber manufacture at Bell Labs
Spring 1974	Bell Labs settles on graded-index fibers with 50 to 100 micrometer cores
June 1975	First commercial continuous-wave semiconductor laser operating at room temperature offered by Laser Diode Labs
Early 1976	Masaharu Horiguchi (NTT Ibaraki Lab) and Hiroshi Osanai (Fujikura Cable) make first fibers with low loss – 0.47 decibel per kilometer – at long wavelengths, 1.2 micrometers
Spring 1976	Lifetime of best laboratory lasers at Bell Labs reaches 100,000 hours (10 years) at room temperature

Summer 1976	Horiguchi and Osanai open third window at 1.55 micrometers
Late 1976	J. Jim Hsieh makes InGaAsP lasers emitting continuously at 1.25 micrometers
1977	General Telephone and Electronics, Bell System, and British Post Office begin sending live telephone traffic through fibers
Late 1977	AT&T and other telephone companies settle on 850 nanometer gallium arsenide light sources and graded-index fibers for commercial systems operating at 45 million bits per second
1977–1978	Low loss at long wavelengths renews research interest in single-mode fiber
August 1978	NTT transmits 32 million bits per second through a record 53 kilometers of graded-index fiber at 1.3 micrometers
Late 1978	NTT Ibaraki lab makes single-mode fiber with record 0.2 decibel per kilometer loss at 1.55 micrometers
1980	Bell Labs publicly commits to single-mode 1.3-micrometer technology for the first transatlantic fiber-optic cable, TAT-8
1982	British Telecom performs field trial of single-mode fiber, changes plans abandoning graded-index in favor of single-mode
January 1, 1984	AT&T undergoes first divestiture, splitting off its seven regional operating companies, but keeping long-distance transmission and equipment manufacture
1985	Single-mode fiber spreads across America to carry long-distance telephone signals at 400 million bits per second and more
1987	Dave Payne at University of Southampton develops erbium-doped fiber amplifier operating at 1.55 micrometers
1988	Linn Mollenauer of Bell Labs demonstrates soliton transmission through 4000 kilometers of single-mode fiber
December 1988	TAT-8 begins service, first transatlantic fiber-optic cable, using 1.3-micrometer lasers and single-mode fiber
February 1993	Nakazawa sends soliton signals over 180 million kilometers, claiming “soliton transmission over unlimited distances”
February 1996	Fujitsu, NTT Labs, and Bell Labs all report sending one trillion bits per second through single optical fibers in separate experiments using different techniques

Dr Javan’s introduction of the first steady helium-neon laser and Dr Kao’s discovery of fiber loss properties were the essential milestones that drove the development of fiberoptic communications. With their work kept as a reference, research activities expanded and a new industry was born, leading to the production of the most advanced cabling solutions that are in use today as a commodity.

What Is an Optical Fiber?

An optical fiber is a flexible filament of very clear glass capable of carrying information in the form of light. Optical fibers are hair-thin structures created by forming pre-forms, which are glass rods drawn into fine threads of glass protected by a plastic coating. Fiber manufacturers use various vapor deposition processes to make the pre-forms. The fibers drawn from these pre-forms are then typically packaged into cable configurations, which are then placed into an operating environment for decades of reliable performance.

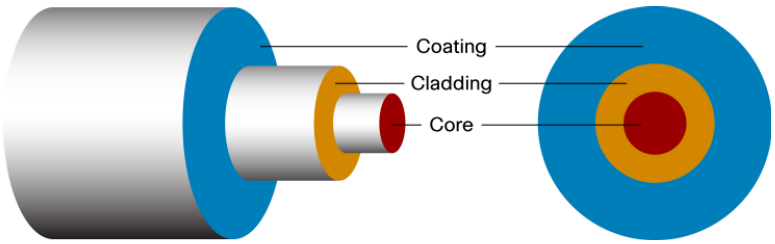
Anatomy of an Optical Fiber

The two main elements of an optical fiber are its core and cladding. The “core”, or the axial part of the optical fiber made of silica glass, is the light transmission area of the fiber. It may sometimes be treated with a “doping” element to change its refractive index and therefore the velocity of light down the fiber.

The “cladding” is the layer completely surrounding the core. The difference in refractive index between the core and cladding is less than 0.5 percent. The refractive index of the core is higher than that of the cladding, so that light in the core strikes the interface with the cladding at a bouncing angle, gets trapped in the core by total internal reflection, and keeps traveling in the proper direction down the length of the fiber to its destination.

Surrounding the cladding is usually another layer, called a “coating,” which typically consists of protective polymer layers applied during the fiber drawing process, before the fiber contacts any surface. “Buffers” are further protective layers applied on top of the coating.

Figure 1. Basic View of an Optical Fiber

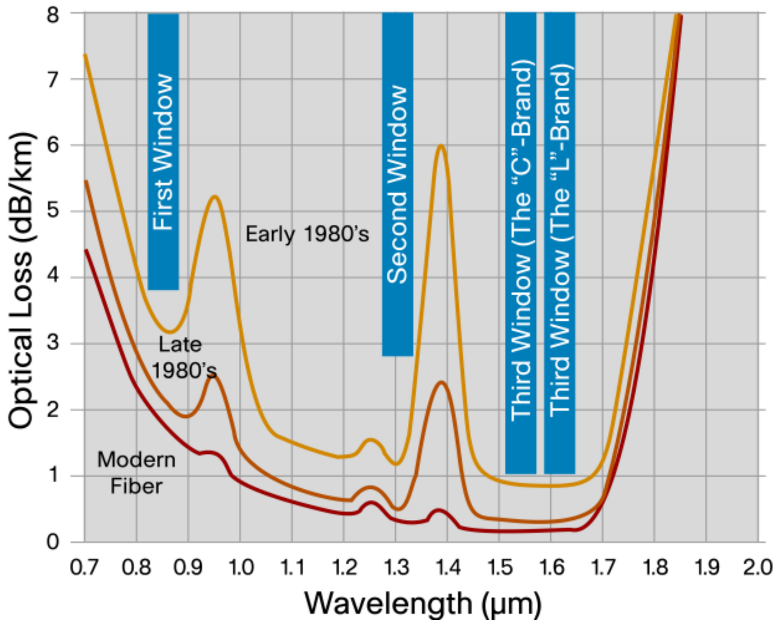


Types of Fiber and Various Parameters

Fibers come in several different configurations, each ideally suited to a different use or application. Early fiber designs that are still used today include single-mode and multimode fiber. Since Bell Laboratories invented the concept of application-specific fibers in the mid-1990s, fiber designs for specific network applications have been introduced. These new fiber designs – used primarily for the transmission of communication signals – include Non-Zero Dispersion Fiber (NZDF), Zero Water Peak Fiber (ZWPF), 10-Gbps laser optimized multimode fiber (OM3), and fibers designed specifically for submarine applications. Specialty fiber designs, such as dispersion compensating fibers and erbium doped fibers, perform functions that complement the transmission fibers. The differences among the different transmission fiber types result in variations in the range and the number of different wavelengths or channels at which the light is transmitted or received, the distances those signals can travel without being regenerated or amplified, and the speeds at which those signals can travel.

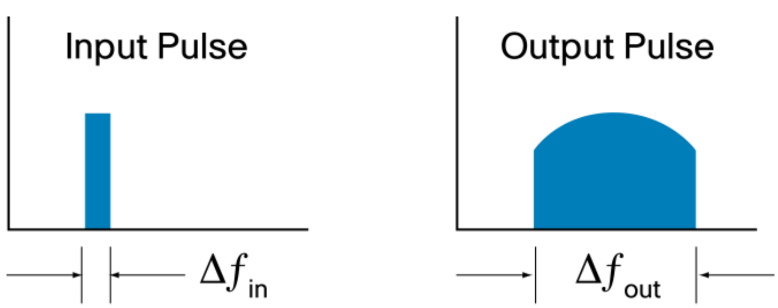
A number of key parameters impact how optical fibers perform in transmission systems. The specifications for each parameter will vary by fiber type, depending upon the intended application. Two of the more important fiber parameters are attenuation and dispersion. Attenuation is the reduction in optical power as it passes from one point to another. In optical fibers, power loss results from absorption and scattering and is generally expressed in decibels (dB) for a given length of fiber, or per unit length (dB/km) at a specific transmission wavelength. High attenuation limits the distance a signal can be sent through a network without adding costly electronics to the system. Figure 2 illustrates the variation of attenuation with wavelength taken over an ensemble of fiber optic cable material types. The three principal windows of operation, propagation through a cable, are indicated. These correspond to wavelength regions where attenuation is low and matched to the ability of a transmitter to generate light efficiently and a receiver to carry out detection. Hence, the lasers deployed in optical communications typically operate at or around 850 nanometers (nm) (first window), 1310 nm (second window), and 1550 nm (third and fourth windows).

Figure 2. Attenuation Versus Wavelength and Transmission Windows



Dispersion is inversely related to bandwidth, which is the information-carrying capacity of a fiber, and indicates the fiber's pulse-spreading limitations. Chromatic dispersion in single-mode fiber links causes pulse spreading because of the various colors of light traveling in the fiber at different speeds, causing a transmitted pulse to spread as it travels down the fiber. Similarly, modal dispersion in multimode fiber links causes pulse spreading because of the geometry of a multimode fiber core allowing for multiple modes of the laser to separate at the fiber interface and propagate simultaneously down the fiber. These modes travel with slight delays relative to each other, causing the transmitted pulse to spread as it travels along the fiber. When pulses spread too far, they overlap and the signal cannot be properly detected at the receiving end of the network. Figure 3 depicts a generic view of pulse spreading.

Figure 3. Pulse Spreading Caused by Dispersion

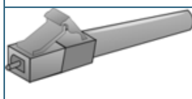
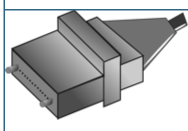
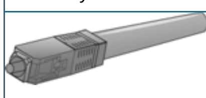
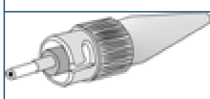


Types of Optical Connectors

The connector is a mechanical device mounted on the end of a fiber optic cable, light source, receiver, or housing. It allows it to be mated to a similar device. The transmitter provides the information-bearing light to the fiber optic cable through a connector. The receiver gets the information-bearing light from the fiber optic cable through a connector. The connector must direct light and collect light. It must also be easily attached and detached from equipment.

There are many different connector types. Table 2 illustrates some types of optical connectors and lists some specifications. Each connector type has strong points. For example, ST connectors are a good choice for easy field installations; the FC connector has a floating ferrule that provides good mechanical isolation; the SC connector offers excellent packing density, and its push-pull design resists fiber end face contact damage during unmating and remating cycles.

Table 2. Common Types of Fiber Optic Connectors

Connector	Insertion Loss	Repeatability	Fiber Type	Applications
 FC	0.5–-1.0 dB	0.2 dB	SM, MM	Datacom, telecom
 LC	0.15 db (SM) 0.10 dB (MM)	0.2 dB	SM, MM	High-density interconnection, datacom, telecom
 MT Array	0.3–1.0 dB	0.25 dB	SM, MM	High-density interconnection
 SC	0.2–0.45 dB	0.1 dB	SM, MM	Datacom, telecom
 ST	Type. 0.4 dB (SM) Type. 0.5 dB (MM)	Type. 0.4 dB (SM) Type. 0.2 dB (MM)	SM, MM	Inter-/intra-building, security, U.S. Navy

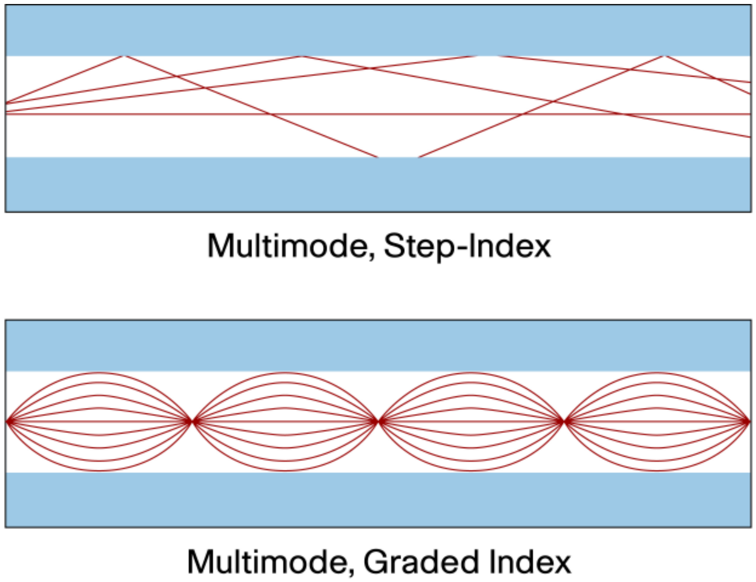
Multimode Fibers

Multimode fiber, the first to be manufactured and commercialized, simply refers to the fact that numerous modes or light rays are carried simultaneously through the waveguide. Modes result from the fact that light will only propagate in the fiber core at discrete angles within the cone of acceptance. This fiber type has a much larger core diameter, compared to single-mode fiber, allowing for the larger number of modes, and multimode fiber is easier to couple than single-mode optical fiber. Multimode fiber may be categorized as step-index or graded-index fiber.

Step-index multimode was the first fiber design but is too slow for most uses, due to the dispersion caused by the different path lengths of the various modes. Step-index fiber is barely used in current telecom and datacom applications.

Graded-index multimode fiber uses variations in the composition of the glass in the core to compensate for the different path lengths of the modes. It offers hundreds of times more bandwidth than step index fiber.

Figure 4. Step-Index and Graded-Index Multimode Fibers



Main Parameters of a Multimode Fiber Link

Core Size and Numerical Aperture

Multimode fibers used in telecom or datacom applications have a core size of 50 or 62.5 microns. This large core size is responsible for the fiber to support multiple transverse electromagnetic modes for a given frequency and polarization. When light enters the fiber, it naturally scatters and the multiple modes travel simultaneously along the path.

The numerical aperture (or NA) of a fiber is the acceptance angle and can be derived from the requirement that the transmitted beam at the core/cladding interface propagates with the critical angle for total internal reflection. If we consider a light beam, coming from air and hitting the core of perpendicularly cut step-index fiber, then the NA is the sine of the maximum angle of an incident beam with respect to the fiber axis, so that the transmitted beam is guided in the core. The NA is determined by the following relation involving the refractive indices of the core and cladding:

- NA = (n¬¬¬¬¬¬¬2core – n2cladding)1/2

For fibers other than step-index fibers, such as the graded-index fiber where the core doesn’t have a constant index profile, an effective numerical aperture is defined based on an equivalent step-index profile. This leads to rather similar mode properties.

Center Wavelength and Reach

Multimode fibers carry optical signals in the first and second telecom windows where the attenuation is minimized. The center wavelength of the laser emitting into the fiber is approximately 850 nm and 1300 nm, respectively.

Depending on transmission speed and center wavelength, different types of lasers may be suitable for applications over multimode fiber. For example LEDs are implemented for Fast Ethernet optical transmissions and low-cost VCSELs are the common choice for Gigabit and 10-Gigabit Ethernet lasers in the 850-nm window. Other Gigabit and 10-Gigabit transceivers emitting in the 1310-nm window may use VCSELs, Fabry-Perot lasers, or DFB lasers.

The reach is the minimum distance guaranteed for a type of laser, over a type of fiber at a certain data rate. The reach over a multimode fiber is usually limited by its modal properties described in further details below. It can be as low as a couple of tens of meters in 10-Gbps links and as much as a couple of kilometers in 100-Mbps links.

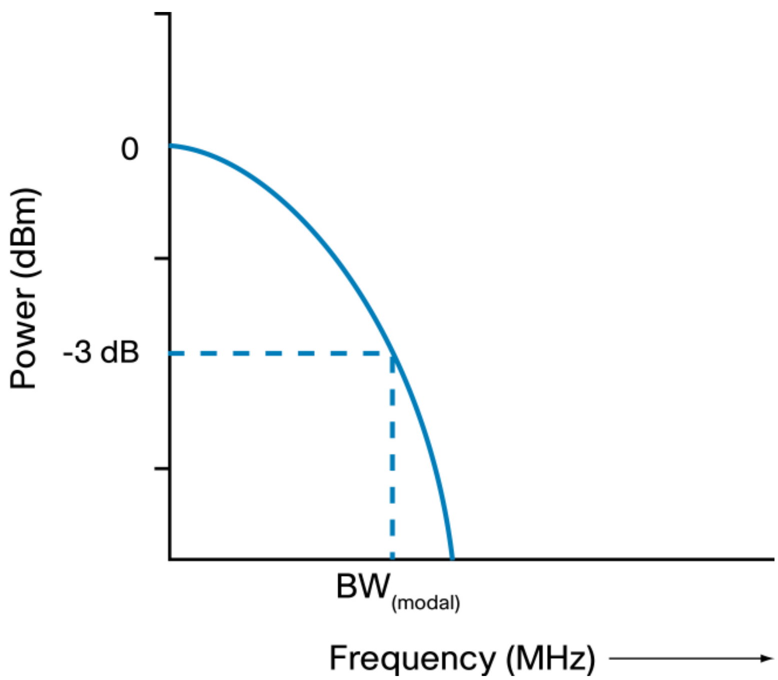
The typical attenuation of a multimode fiber is of about 1 to 1.5 decibels (dB) per kilometer (km).

Modal Bandwidth, Channel Impulse Response, and Modal Dispersion

One key characteristic of a multimode fiber is its modal bandwidth. It represents the capacity of a fiber to transmit a certain amount of information and is expressed in MHz*km. The modal bandwidth of a multimode fiber is determined from the optical output frequency spectrum. The frequency at which the amplitude drops 3 dB relative to the zero frequency component of the fiber is defined as the –3dB bandwidth, or modal bandwidth of the fiber (see Figure 5).

Alternately, the effective modal bandwidth (EMB) is the actual modal bandwidth observed in a given link of a certain length characterized with reference to a specific source.

Figure 5. Output Power Frequency Spectrum



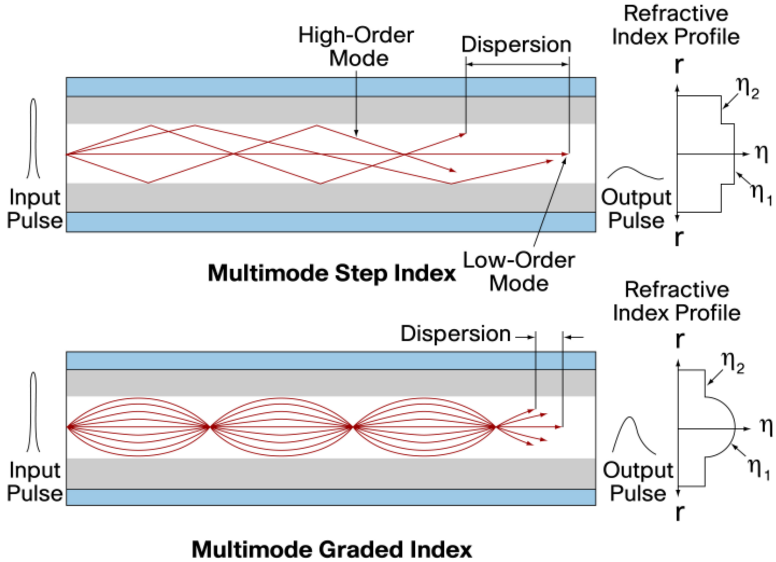
Tightly related to the modal bandwidth, the channel impulse response is yet another characteristic of a multimode fiber link. It depicts the pulse spreading (or modal dispersion or differential modal delay) suffered by a light signal traveling along the fiber path. Figure 6 is an illustration of modal dispersion and channel impulse response.

With all the different modes of propagation allowed in a multimode fiber, different rays travel different distances and take different amounts of time to transit the length of a fiber. This being the case, if a short pulse of light is injected into a fiber, the various rays emanating from that pulse will arrive at the other end of the fiber at different times. The output pulse will be of longer duration than the input pulse.

In the case of a graded-index multimode fiber, the index of refraction across the core is gradually changed from a maximum at the center to a minimum near the edges, hence the name graded index. This design takes advantage of the phenomenon that light travels faster in a low-index-of-refraction material than in a high-index material. The light rays or modes of propagation that travel near the edges of the core travel faster for a longer distance, thereby transiting the fiber in approximately the same time as the “low-order modes” or rays traveling more slowly near the center of the core.

If a short pulse of light is launched into the graded-index fiber, it may spread some during its transit of the fiber, but much less than in the case of a step-index fiber. Therefore, multimode graded-index fibers have the ability to transport pulses closer together without spreading into each other than step-index fibers. They can support a much higher bit rate or bandwidth. Typical bandwidths of graded index fibers range from 200 MHz*km to well over one GHz*km. The actual bandwidth depends on how well a particular fiber’s index profile minimizes modal dispersion and on the wavelength of light launched into the fiber.

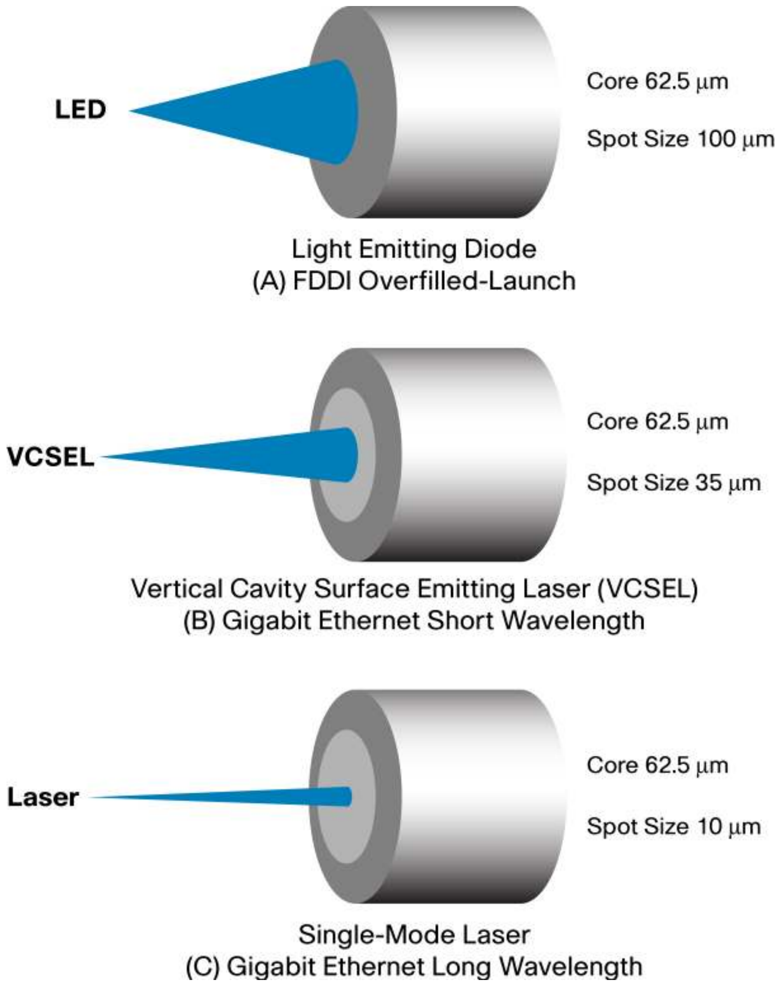
Figure 6. Impulse Response and Modal Dispersion of Multimode Graded-Index and Step-Index Fibers



Launch Conditions, OFL Bandwidth, and Mode Conditioning Patch Cords

Until Gigabit Ethernet systems became available, the fiber most widely used in LAN and private network applications was the FDDI-grade 62.5 µm core fiber with 160 MHz*km bandwidth at 850-nm wavelength and 500 MHz*km at 1310 nm. The bandwidth of these fibers has been measured with an overfilled-launch (OFL) light source, which illuminates the entire core of the fiber, to simulate the performance of the fiber when used with the broad illumination pattern of light-emitting diode (LED) light sources. More recently, many networks are being designed for use with Gigabit Ethernet systems utilizing laser light sources, which have a much smaller spot of light illuminating the fiber core at smaller incidence angles than LED light sources. Figure 7 depicts the difference between these launch conditions.

Figure 7. OFL Light Source Versus Laser Light Source



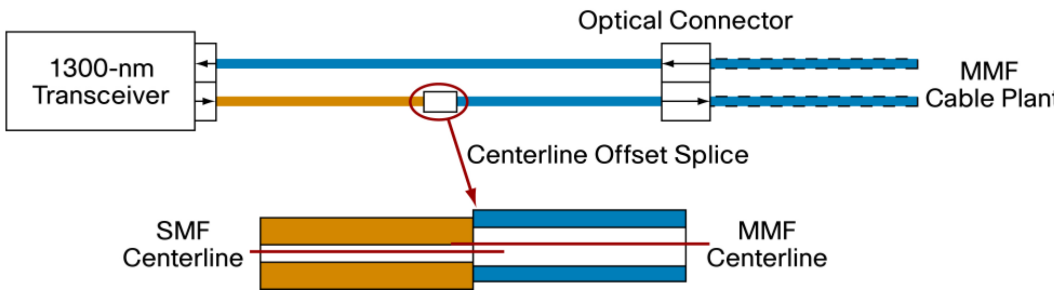
The Vertical Cavity Surface Emitting Laser (VCSEL) does not energize as many dispersive modes of the fiber waveguide as does the overfilled-launch of an LED, so the fiber modal dispersion and bandwidth performance are different than might be expected from the overfilled-launch measurements.

In laser-based Gigabit and 10-Gigabit Ethernet transmissions, where the laser emits in the second window (1300 nm), the launch is restricted to a small area of the core, and only a small number of modes are launched in comparison to LED- or VCSEL-based transmissions. For this case, since a small number of modes are traveling, any fiber imperfection can cause significant intermodal delays, thus jeopardizing the performance of the transmission link.

As a result a solution was developed to ensure that the launch from such edge emitting lasers would withstand any of the imperfections that may exist in the installed base. A criterion that needed to be considered was that 1000BASE-LX transceivers need to operate over single-mode fiber and multimode fiber so it was not possible to develop a multimode-fiber-only solution within the transceiver. The method of implementing these launches for multimode fiber applications is to use a mode-conditioning patch cord.

The solution is to develop a launch that excites a large number of modes in the multimode fiber so that no individual modes can impact the transmission performance. This can be achieved by the relatively simple method of offsetting the launch into the fiber away from the center. This can be visualized in two ways. By launching the light away from the center it misses the area where most of the manufacturing imperfections occur. The second, and more accurate explanation, is that by launching off center, the symmetry of the launch is broken and a large number of modes are excited which reduces the impact of any manufacturing imperfections. The mode conditioning patch cord based on the offset launch is illustrated in Figure 8.

Figure 8. Mode Conditioning Patch Cord



The launch of the light coming out of the Gigabit transceiver begins on a single-mode fiber. The single-mode fiber is coupled into the multimode fiber with a precise core misalignment. This precise misalignment causes the light entering the multimode fiber to launch a high number of modes, giving the cable its mode-conditioning properties.

As a result, the OFL bandwidth specified for the second window can be met regardless of potential fiber imperfections.

Types of Multimode Fiber and Associated Transceivers

Table 3 summarizes the different fiber types defined by various standard bodies.

Table 3. Various Types of Multimode Fiber

Standards Body	Document	Notes
TIA – Telecommunications Industry Association	492AAAA	62.5 µm fibers with 160/500 MHz.km OFL BW
	492AAAB	50 µm fibers with 500/500 MHz.km OFL BW
	492AAAC	Laser-optimized 50 µm fibers with 2000 MHz.km EMB at 850 nm
IEC – International Electrotechnical Commission	60793-2-10	A1a.1 fiber – 50 µm fibers with a range of OFL BW
		A1a.2 fiber – Laser-optimized 50 µm fibers with 2000 MHz.km EMB at 850 nm
		A1b fiber – 62.5 µm fibers with a range of OFL BW
ISO – International Standards Organization	11801	OM1 fiber – 200/500 MHz.km OFL BW (in practice OM1 fibers are 62.5 µm fibers)
		OM2 fiber – 500/500 MHz.km OFL BW (in practice OM2 fibers are 50 µm fibers)
		OM3 fiber – Laser-optimized 50 µm fibers with 2000 MHz.km EMB at 850 nm

Cable types are defined slightly differently by each standard body. In practical situations, four main fiber types are commonly used:

- FDDI-grade is the legacy multimode fiber with 160 MHz*km bandwidth at 850 nm
- OM1 is another 62.5 micron fiber with little bit more bandwidth

- OM2 is the traditional 50 micron fiber
- OM3 is the laser-optimized fiber, ideally suited for VCSEL-based transmitters at 850 nm

Table 4 summarizes various optical interfaces and their performance over the different fiber types. The table is directly derived from the IEEE 802.3-2005 standard and specifies the maximum reach achievable over each fiber type and the requirement for a mode conditioning patch cord (MCP).

Table 4. Multimode Transceiver/Fiber Type Compatibility Matrix

Interface Type	Wavelength (nm)	Fibers Supported	Reach (m)	MCP Requirement
1000BASE-SX	850	FDDI-grade	220	No
		OM1	275	No
		OM2	550	No
		OM3	Not specified	
1000BASE-LX	1300	FDDI-grade	550	Yes
		OM1	550	Yes
		OM2	550	Yes
		OM3	Not specified	
10GBASE-SR	850	FDDI-grade	26	No
		OM1	33	No
		OM2	82	No
		OM3	300	No
10GBASE-LX4	1300	FDDI-grade	300	Yes
		OM1	300	Yes
		OM2	300	Yes
		OM3	Not specified	
10GBASE-LRM	1300	FDDI-grade	220	Yes
		OM1	220	Yes
		OM2	220	Yes
		OM3	220	No

These performance levels are guaranteed. If we go beyond the standard, longer reaches may be achievable depending on the quality of each link. Fiber quality can vary for a specific type due to the aging factor or to the random imperfections it was built with. In order to really know if a link can work, the rule is to try and see if the performance is satisfactory. The link should be either error-free for critical applications, or the bit error should remain below 10-12 as per minimum standard requirement.

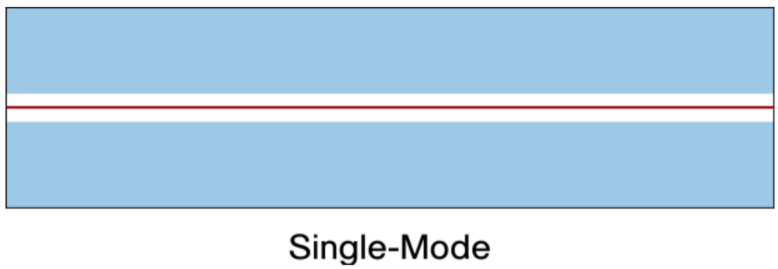
As an example it may be possible to reach much longer distances than 550m with an OM3 laser-optimized fiber and 1000BASE-SX interfaces. Also, it may be possible to reach 2 km between two 1000BASE-LX devices over any fiber type with mode conditioning patch cords properly installed at both ends.

In addition, future fibers are already under study. Manufacturers are generally working on improving the bandwidth in the 850-nm window, where low-cost VCSEL-based transceivers are an attractive alternative for new deployments. The OM3+ with a modal bandwidth of 4700 MHz*km is already available, but the IEEE would need to approve its standardization.

Single-Mode Fibers

Single-mode (or monomode) fiber enjoys lower fiber attenuation than multimode fiber and retains better fidelity of each light pulse, as it exhibits no dispersion caused by multiple modes. Thus, information can be transmitted over longer distances. Like multimode fiber, early single-mode fiber was generally characterized as step-index fiber meaning the refractive index of the fiber core is a step above that of the cladding rather than graduated as it is in graded-index fiber. Modern single-mode fibers have evolved into more complex designs such as matched clad, depressed clad, and other exotic structures.

Figure 9. Single-Mode Fibers



Main Parameters of a Single-Mode Fiber Link

Core Size and Numerical Aperture

Single-mode fiber shrinks the core down so small that the light can only travel in one ray. The typical core size of a single-mode fiber is 9 microns.

Since only one mode is allowed to travel down the fiber path, the total internal reflection phenomenon does not occur and the concept of numerical aperture is reduced to its definition (the same as for multimode fibers). It measures the core and cladding refractive indices difference but has little impact on the information propagation. The NA for a single-mode fiber is usually smaller than for a multimode fiber.

Center Wavelength and Reach

Single-mode fibers carry optical signals in the second and third telecom windows where attenuation is minimized. The center wavelength of the laser emitting into the fiber is approximately 1310 nm and 1550 nm, respectively. CWDM and DWDM channels operate over single-mode fibers in the third window with a wavelength drifting tolerance stricter than for non-WDM channels.

Common lasers suitable for applications over single-mode fiber are Fabry-Perot and distributed feedback (DFB) lasers.

As for multimode fibers, the reach is the minimum distance guaranteed for a type of laser, over a type of fiber at a certain data rate. The reach over a single-mode fiber is generally limited by accrued chromatic and polarization-mode dispersion, which are typically of greater impact as data rates are higher. Additionally, the reach can also be limited by the degradation of optical signal over noise ratio (OSNR) in the case of amplified links. Finally Fabry-Perot lasers are used for shorter-reach applications as their spectrum width is large and more subject to dispersion. DFB lasers are typically used for longer reaches as their spectrum width is narrow and therefore relatively less subject to dispersion.

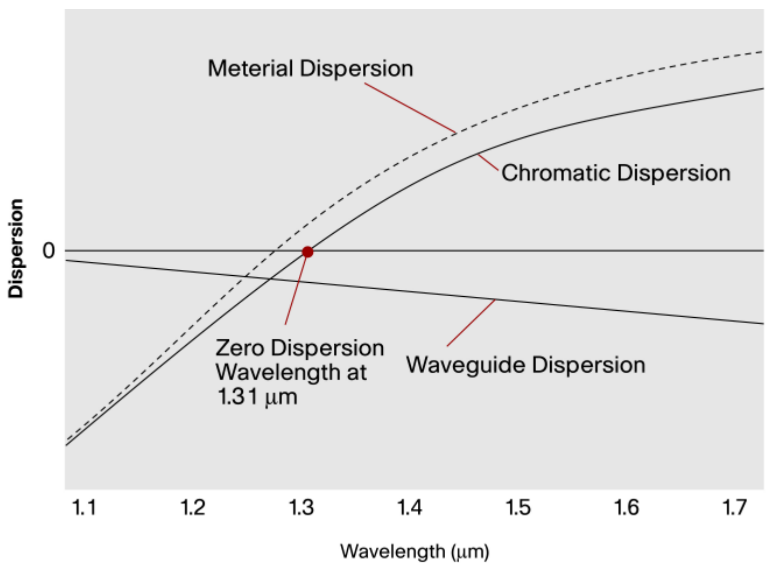
The attenuation of a single-mode fiber is of about 0.4 dB per km in the second window and 0.25 dB per km in the third window.

Dispersion

Dispersion affects single-mode fiber links and as for multimode fiber links, the consequence of the phenomenon is pulse spreading. In this case this is not due to the modal properties of the single-mode fiber since it can only transport one and only one mode. Instead polarization-mode dispersion (PMD) and chromatic dispersion (CD) are responsible for pulse spreading. As for the case of multimode fibers, pulse spreading takes more importance with higher data rates as the pulse unit interval becomes smaller and risks of pulses overlapping are greater.

Chromatic dispersion represents the fact that different colors or wavelengths travel at different speeds, even within the same mode. Indeed, a transmitted wavelength is not a perfect peak and instead displays a finite spectral width. Therefore it is a small wavelength range that is transmitted, and components within this range travel at slightly different speeds. This results in the spreading of pulses traveling over a significant distance. This distance varies depending on the fiber type, the laser type, and the data rate. Chromatic dispersion is the result of material dispersion and waveguide dispersion. Figure 10 shows chromatic dispersion along with key components waveguide dispersion and material dispersion.

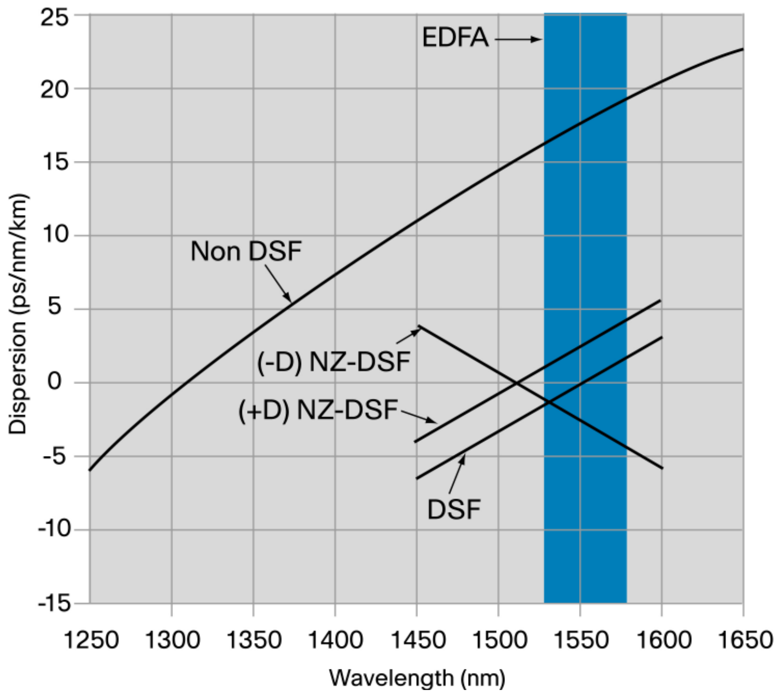
Figure 10. Chromatic Dispersion in a Standard Single-Mode Fiber



Dispersion is a function of the wavelength. Standard single-mode fibers have a zero dispersion at 1310 nm. Therefore, 1310-nm transmitters are not subject to chromatic dispersion. Only 1550-nm, CWDM, and DWDM transmissions over standard single-mode fiber are affected by this phenomenon. However, the third telecom window is very advantageous and used more and more frequently because of lower fiber loss properties in this region and the ability to amplify optical signals with erbium-doped fiber amplifiers (EDFA). This implies the need for new fiber types or chromatic dispersion compensation techniques.

The common single-mode fiber is defined in ITU G.652 standard. In order to eliminate the problems encountered by transmissions in the third window, other fiber types were developed. Dispersion-shifted fibers (DSF) with a zero dispersion at 1550 nm were defined in ITU G.653. Shifting the zero dispersion in the 1550-nm window can be simply achieved by modifying the refractive index profile of the core. However, even though this fiber type eliminates the problem for transmissions of single wavelengths at 1550 nm, it is not suitable for wavelength multiplexing applications as WDM transmissions can be affected by another non-linear effect called four-wave mixing. This led to the definition of non-zero dispersion shifted fibers (NZDSF) in the ITU G.655 standard. For this fiber type, the zero dispersion is shifted just outside the C-Band, usually around 1510 nm. This helps limiting the chromatic dispersion as the zero dispersion remains close enough to the transmission band, and the other non-linear effects such as four-wave mixing because the zero dispersion remains far enough from the transmission band. There are two types of NZDSF, known as (-D)NZDSF and (+D)NZDSF. They have respectively a negative and positive slope versus wavelength. Figure 11 depicts the dispersion properties of the four main single-mode fiber types. The typical chromatic dispersion of a G.652 compliant fiber is 17ps/nm/km.

Figure 11. Chromatic Dispersion of Single-Mode Fiber Types

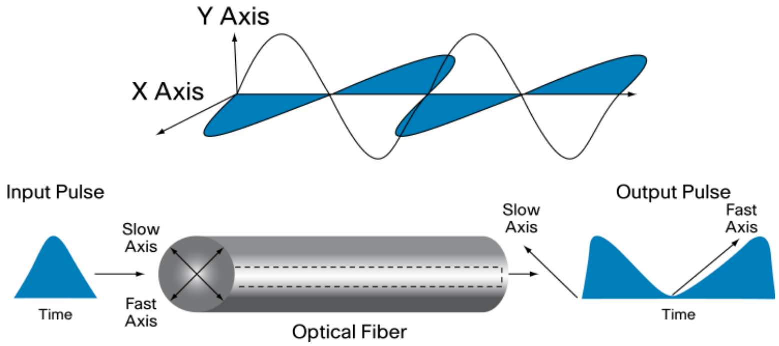


Chromatic dispersion is deterministic, linear, not affected by the environment, and can be compensated through various means. On the other hand, polarization-mode dispersion (PMD) is a stochastic non-linear phenomenon deriving from the little asymmetries of optical fibers. It is subject to environmental changes (such as temperature, fiber movements, etc.) and cannot be easily compensated.

Single-mode fibers support two perpendicular polarizations of the transmitted signal. If fibers were perfectly round and free from all stresses, both polarization modes would propagate at exactly the same speed, resulting in zero PMD. However, practical fibers are not perfect, thus, the two perpendicular polarizations may travel at different speeds and, consequently, arrive at the end of the fiber at different times. As such, the fiber is said to have a fast axis and a slow axis. The difference in arrival times, normalized with length, is known as PMD.

Figure 12 depicts the propagation of two polarization modes along a fiber. Let’s assume X is the slow axis and Y is the fast axis. The index of refraction of the X axis, nx, is greater than the index of refraction of the Y axis, ny. The two modes travel at different speeds and an injected pulse can be distorted and even duplicated when the signal reaches the other end of the fiber. This distortion of the pulse is referred to as pulse splitting.

Figure 12. Pulse Splitting Due to PMD in a Single-Mode Fiber



It is widely recognized that transmissions modulated at 40 Gbps impose very strict requirements on the fiber plant and systems deployed in the field. Even at 10 Gbps, PMD can cause serious limitations on poor-quality fiber links deployed before 2001. Additionally, only external modulation can be implemented in order to achieve “pure” 40-Gbps line rates from a single laser. This bulky solution can only be adopted in the case of transponder designs. As a result, current designs for 40-Gbps and 100-Gbps transceivers are based on directly modulated 10-Gbps laser designs and integrated WDM technology.

OSNR for Amplified Links

Optical signal over noise ratio (OSNR) is yet another parameter to consider in single-mode fiber transmissions. It is essentially applicable to DWDM links amplified with EDFAs used as boosters, intermediate repeaters, or pre-amplifiers. Although optical amplifiers are critical to reach longer distances without the need for costly optical-electrical-optical conversions, they also produce very broadband amplified spontaneous emissions (ASE) resulting in an addition of a noise floor mixing with the transmitted signal in the third telecom window. Standards defining DWDM applications would require that the OSNR remains large enough so that a receiver is able to distinguish data pulses from the noise floor.

Types of Single-Mode Fiber and Associated Transceivers

Tables 5, 6, and 7 are specifications of G.652C, G.653A, and G.655C-compliant fibers, respectively. G.652C is the most commonly used single-mode fiber.

As a reminder, G.652-compliant fibers are non-dispersion shifted (NDSF) traditional single-mode fibers. G.653-compliant fibers are dispersion shifted fibers (DSF) with a zero dispersion centered at 1550 nm. G.655-compliant fibers are non-zero dispersion shifted fibers (NZDSF) with a zero dispersion usually centered at 1510 nm.

Table 5. ITU G.652C Specifications for NDSF Type

Fiber Attributes		
Attribute	**Detail**	**Value**
Mode field diameter	Wavelength	1310 nm
	Range of nominal values	8.6–9.5 µm
	Tolerance	+/- 0.6 µm
Cladding diameter	Nominal	125.0 µm
	Tolerance	+/- 1 µm
Core concentricity error	Maximum	0.6 µm
Cladding non-circularity	Maximum	1.0%
Cable cutoff wavelength	Maximum	1260 nm

Macrobend loss	Radius	30 mm
	Number of turns	100
	Maximum at 1625 nm	0.1 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient	λ0min	1300 nm
	λ0max	1324 nm
	S0max	0.092 ps/(nm2*km)
Cable Attributes		
Attribute	**Detail**	**Value**
Attenuation coefficient	Maximum from 1310 nm to 1625 nm	0.4 dB/km
	Maximum at 1550 nm	0.3 dB/km
PMD coefficient	M	20 cables
	Q	0.01%
	Maximum PMDQ	0.5 ps/√km

Table 6. ITU G.653A Specifications for DSF Type

Fiber Attributes		
Attribute	**Detail**	**Value**
Mode field diameter	Wavelength	1550 nm
	Range of nominal values	7.8–8.5 µm
	Tolerance	+/-0.8 µm
Cladding diameter	Nominal	125 µm
	Tolerance	+/-1 µm
Core concentricity error	Maximum	0.8 µm
Cladding non-circularity	Maximum	2.0 %
Cable cutoff wavelength	Maximum	1270 nm
Macrobend loss	Radius	30 mm
	Number of turns	100
	Maximum at 1625 nm	0.5 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient	λmin	1525 nm
	λmax	1575 nm
	Dmax	3.5 ps/(nm*km)
	λ0min	1500 nm
	λ0max	1600 nm
	S0max	0.085 ps/nm2*km
Cable Attributes		
Attribute	**Detail**	**Value**
Attenuation coefficient	Maximum at 1550 nm	0.35 dB/km
PMD coefficient	M	20 cables
	Q	0.01 %
	Maximum PMDQ	0.5 ps/√km

Table 7. ITU G.655C Specifications for NZDSF Type

Fiber Attributes		
Attribute	**Detail**	**Value**
Mode field diameter	Wavelength	1550 nm
	Range of nominal values	8–11 µm
	Tolerance	+/-0.7 µm
Cladding diameter	Nominal	125 µm
	Tolerance	+/-1 µm
Core concentricity error	Maximum	0.8 µm
Cladding non-circularity	Maximum	2.0%
Cable cutoff wavelength	Maximum	1450 nm
Macrobend loss	Radius	30 mm
	Number of turns	100
	Maximum at 1625 nm	0.5 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient	λmin and λmax	1530 nm and 1565 nm
	Minimum value of Dmin	1.0 ps/(nm*km)
	Maximum value of Dmax	10.0 ps/(nm*km)
	Sign	Positive or negative
	Dmax - Dmin	≤ 5.0 ps/(nm*km)
Cable Attributes		
Attribute	**Detail**	**Value**
Attenuation coefficient	Maximum at 1550 nm	0.35 dB/km
	Maximum at 1625 nm	0.4 dB/km
PMD coefficient	M	20 cables
	Q	0.01%
	Maximum PMDQ	0.2 ps/√km

Table 8 is a summary of various optical interfaces and the single-mode fiber types recommended for deployment.

Table 8. Single-Mode Transceiver/Fiber Type Compatibility Matrix

Interface Type	Wavelength (nm)	Typical Reach* (km)	NDSF	DSF	NZDSF
1000BASE-LX **1000BASE-BX** **10GBASE-LR** **10GBASE-LW** **10GBASE-LX4**	1310	10	Yes	No	No
10GBASE-ER	1550	30–40	Yes	Yes	Yes
1000BASE-ZX **10GBASE-ZR**	1550	80–100	Yes	Yes	Yes
CWDM	1470 to 1610	80–120**	Yes	No	Yes
DWDM	1530 to 1565	80–100**	Yes	No	Yes

* The reaches in this table illustrate typical performance observed in the field. They may vary with the rate and fiber type and should not be considered as guaranteed.
** In unamplified point-to-point applications.

Link Budget Evaluation

Evaluating a link budget is equivalent to calculating the total loss suffered by a transmitted signal across various components and along fiber channels with reference to the minimum receiver power required to maintain normal operation. Calculating the link budget helps network architects to identify the feasibility of a physical-layer deployment. This section depicts the rules to be applied in order to evaluate link budget. Three cases can be distinguished.

Link Budget for Point-to-Point Transmissions over Multimode Fibers

In this first case, the rule is fairly simple. A few parameters need to be taken into account:

- The minimum transmit power guaranteed (minTx), expressed in dBm
- The minimum receive power required (minRx), expressed in dBm
- The loss of optical connectors and adapters (L), expressed in dB
- The number of connectors and adapters (n)
- The normalized fiber loss (FL), expressed in dB/km
- The reach or distance to be achieved (d), expressed in km

With these parameters, the link budget (LB) expressed in dB is given as follows:

- (LB) = (minTx) – (minRx)

This value needs to be compared to the total loss (TL) suffered by the transmitted signal along the given link, and expressed in dB:

- (TL) = n*(L) + d*(FL)

If (LB) is greater than (TL), then the physical deployment is theoretically possible.

In these calculations n is at least equal to 2 since there are a minimum of 2 connectors at each end, (L) is typically around 0.5 to 1 dB, and (FL) is of about 1 to 1.5 dB per km.

Link Budget for Point-to-Point Transmissions over Single-Mode Fibers

In this second case, the calculations are exactly similar to the previous case. Only the numerical values will differ.

For single-mode point-to-point transmissions, n is at least equal to 2, (L) is typically around 0.3 to 0.5 dB, and (FL) is of about 0.4 dB per km in the second window and about 0.25 dB per km in the third window.

Link Budget for WDM and Amplified Transmissions over Single-Mode Fibers

In the case of WDM transmissions, passive modules are used to multiplex and demultiplex various wavelengths respectively before and after the signal propagates along the fiber channel. These passive modules introduce additional insertion losses suffered by the signal transmitted.

Additionally, the signal may be amplified and compensated for dispersion, and in this case, the amplifier gain and the dispersion compensation unit’s loss need to be taken into account. Dispersion and OSNR penalties suffered by the receiver shall be considered as well.

Therefore all the parameters needed for a proper link budget evaluation are:

- The minimum transmit power guaranteed (minTx), expressed in dBm
- The minimum receive power required (minRx), expressed in dBm
- The loss of optical connectors and adapters (L), expressed in dB

- The number of connectors and adapters (n)
- The normalized fiber loss (FL), expressed in dB/km
- The reach or distance to be achieved (d), expressed in km
- The loss of passive add/drop modules (A and D), expressed in dB
- The gain of the amplifier (G), expressed in dB
- The penalty suffered by the receiver (P), expressed in dB
- The loss of a dispersion compensation unit (DCU), expressed in dB

With these parameters, (LB) is given as for previous cases:

- (LB) = (minTx) – (minRx)

And the total loss is expressed as follows:

- (TL) = n*(L) + d*(FL) + (A) + (D) – (G) + (DCU) + (P)

Here again, if (LB) is greater than (TL), then the physical deployment is feasible.

Please note that for simplicity, only one amplifier, one dispersion compensation unit, and one set of add/drop modules are considered in this example. If more devices are planned to be deployed, their loss or gain should be added or subtracted accordingly in order to calculate (TL).

References

1. City of Light: The Story of Fiber Optics, Jeff Hecht, Oxford University Press, New York, 1999
2. Fiber Optic Data Communications for the Premises Environment, Dr Kenneth S. Schneider
3. IEEE Std 802.3aq-2006
4. IEEE Std 802.3-2005
5. ITU-T Std G.652, Characteristics of a single-mode optical fibre and cable
6. ITU-T Std G.653, Characteristics of a dispersion-shifted single-mode optical fibre and cable
7. ITU-T Std G.655, Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable
8. http://www.ofsoptics.com
9. http://www.corning.com
10. http://www.fiber-optics.info
11. http://www.rp-photonics.com
12. http://www.occfiber.com

Printed in USA

C11-463661-00 04/08